SURVEY AND INVESTIGATION OF PERFORMANCE OF SUPERSTRUCTURE OF LONG SPAN BRIDGES IN CHINA

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ABSTRACT

With the rapid development of China's economy in the past three decades, requirements for construction of infrastructure for transportation have been enhanced and a great many long-span bridges have been built. Internationally, it can be boasted that China is one of the countries with the most long-span bridges. However, inadequate performance in long span bridges is often observed in field investigations, such as, excessive deflection in the mid-span, cracking of the concrete, cable corrosion in cable-stayed bridges, suspender cable corrosion in suspension bridges, and the corrosion of reinforced steel in the concrete resulting in the scaling and spalling of the concrete cover. This arouses the concern for the safety, serviceability, durability, service life, life cycle cost of maintenance and rehabilitation of long span bridges. A survey was made on the working condition of long span bridges in China. The causes resulting in deterioration of long span bridges are examined and measures for prolonging the service life of long span bridges in view of design, construction and maintenance are proposed.

KEYWORDS

Long-span bridges, survey, typical damage, deflection, crack, corrosion, durability, service life.

INTRODUCTION

With the rapid development of the economy in China in the past three decades, it has necessitated an increase in the construction of transportation infrastructure and a great many long-span bridges have been built. According to the statistics, by the end of 2013, the number of highway bridges reached 735,300 and the total length up to 39,778,000 m, in which 3,075 are large span bridges with a total length greater than 1,000 m of multi-span and total length greater than 150 m of single-span, and the total length 5,461,400 m. By July 2014, the top ten bridges with the greatest main span in the world, China make up six for cable-stayed bridge, five for suspension bridge, six for arch bridge and seven for prestressed concrete girder bridge. We can say indescribably that great achievement has been made in the design and construction of long span bridges in China.

However, it is another scenario for the long span bridges after years of operation. Survey and investigation reveals that more than 70% of the bridges show various degrees of deterioration (Lu 2011), including excessive deflection in mid-span, cracking in the box girder, corrosion of cables and so on. This unexpected poor performance raises the concern of the safety, serviceability, and the life cycle maintenance cost of bridges. Therefore, it is important to identify and analyze the causes of the deterioration of long-span bridges, so as to recheck and revise the design and construction code, and provide a range of precautionary and measures to mitigate the degrading process, ensuring the safety and prolonging the service life of bridges.

This paper summarizes the typical damage and defects in the superstructures of long-span bridges in China, and analyzes the causes resulting in the deterioration of bridges and briefs the precautionary measures to avoid and mitigate the degradation.

TYPICAL DEFICIENCY OF LONG-SPAN BRIDGE

Excessive Midspan Deflections of Main Girder

As reported in the literature, there is a worldwide problem with the excessive deflection of the main girder of long span bridges. This phenomenon is more remarkable for the long span bridges in China concerning such features as:

- deflection with an accelerating, decreasing or constant growth rate over time,
- long-time deflections much larger than the design value (Xie *et al*. 2007; Bao and Zhou 2009).

Table 1 shows 11 examples of excessive long-time deflection of long-span prestressed concrete bridges which represent the typical deformation performance of long-span bridges in China. All the bridges surveyed in table 1, except Yuanshan Bridge which is hinged rigid frame bridge with T type section, are continuous rigid frame bridges with girder section of single-cell box. The construction methods of these bridges include three-dimensional prestress, cast-in-situ, cantilever casting construction, internal prestress and post-tensioned. Sugute Bridge used both internal prestress and external prestress in mid-span.

Table 1 Deflection of several long-span prestressed concrete bridges in China

No.	Bridge	Location	Completion	Span/m	Maximum Deflection/cm	Served time/year
1	Secondary channel of Humen Bridge	Guangdong	1997	150+270+150	22.2	7
2	Huangshi Yangtze River Bridge	Hubei	1995	162.5+3×245+162.5	30.5	7
3	Sanmenxia Yellow River Highway Bridge	Shanxi to Henan	1992	105+4×140+105	22	10
4	Jinsha Bridge	Guangdong	1994	66+120+66	22	6
5	Dongming Yellow River Bridge	Shandong	1993	75+7×120+75	14.6	—
6	Fenglingdu Yellow River Bridge	Shanxi	1994	87+7×114+87	29	14
7	Yajisha Bridge	Guangdong	2000	86+160+86	23	3
8	Jiangjin Yangtze River Bridge	Chongqing	1997	140+240+140	31.7	10
9	Sugute Bridge	Yunnan	2007	65+110+65	28	—
10	Luoxi Bridge	Guangdong	1988	65+125+180+110	6.4	3
11	Yuanshan Bridge	Taiwan	1977	75+150+2×142.5+118	63	—

Note: "—" means it is not mentioned in the literature.

Numerous aspects are responsible for the excessive deflection of long-span bridges, and the main causes are as follows:

Shrinkage and creep of concrete

The uncertainties associated with the creep and shrinkage of concrete are the main obstacle for the prediction of long time deformation (Xie *et al*. 2007). Much research has been devoted to concrete creep and shrinkage and many prediction models, including CEB-FIP, ACI, JSCE, GL and B3, have been proposed. Although great progress has been made and various improved theoretical models have been developed, in the best situation, the coefficient of variation is 20% for the creep compliance and 35% for the shrinkage strain, which is far from expectation (Takács 2002). A linear concrete creep theory is adopted for the long-term deflection prediction in the bridge design. With this hypothesis, the concrete creep tends to be constant after several years of completion. But the fact is that the long-term deflection caused by concrete creep is far greater than the design values, which implies that inappropriate model may be employed or nonlinear creep occurred, at least in local position. At this point of view, concrete creep prediction is still a great challenge we have to be faced.

In recent years, on the other hand, with the utilization of high strength concrete and reinforcing steel and optimization for the concrete box girder, the plate member becomes thinner and thinner, leading to the effects of shrinkage and creep of the structure becoming more and more obvious (Wang and Shi 2006). Besides, pumping concrete is now widely used for fabricating the large prestressed concrete columns, for the purpose of ensuring the flowability of concrete with superplasticizer as a commonly used additive. If the vibration is not sufficient in intensity and time, the formation of voids will result in significant shrinkage and creep of concrete (Wang *et al*. 2010).

Cracks in girders

Various cracks in girders contribute significantly also to the long-time deflection of the long-span bridges, which may be exhibited in the following aspects (Qiao 2011):

- reducing the stiffness of the girders,
- resulting in internal force redistribution in the cracked section and decrease of the depth in compression, which in turn increase the stress of concrete in compression and tendon, leading to further creep and

- prestress loss,
- expanding the cracks by overloaded vehicles, eventually increasing deflection.

Decrease of Longitudinal Effectiveness of Prestressing in the Girder

It is the third reason which contributes to the excessive long-time deflection of long-span bridges that the decrease of longitudinal effective prestressing of bottom slab in the sagging moment region and top slab in the negative moment region (Zhan and Chen 2005). In the operation of a bridge, prestressing in the tendon of girder lost with time, decompressing the concrete gradually. It is equivalent to applying an additional bending moment in the girder, which intensifies the deflection of midspan (Bai 2007). Furthermore, the interaction among shrinkage, creep, cracking and prestressing loss exacerbates the long-time deflection of the bridges (Wang *et al*. 2010). Much research has been devoted to prestressing loss. Calculation method of prestressing loss is different from country to country. Up to date, however, no simple, accurate and unified approach has been found.

Shear lag

In a box girder, shear flow transmits from vertical webs to the horizontal flanges. This phenomenon is called shear lag which causes in-plane shear deformation of the flanges and results in unpredicted extra longitudinal displacement at the web-flange junction. The shear lag produces out-of-plane warping of an initially planar cross section and a significant non-uniformity of the distribution of the longitudinal normal stress across the flange width. Despite considerable research on shear lag has been made (Krístek *et al*. 1987; Luo and Li 2000; Luo and Li 2002), long-term deflection caused by shear lag is considered insufficiently in design. Nowadays, 'Wide Single Cell Box' is a commonly used format in the design of bridge girder, which possesses greater span to width ratio and always generates a lager lateral force, leading to a difficulty of structural analysis.

Apart from the aforementioned aspects, the excessive long-time deflection is also associated with thermal effect, overload vehicle, corrosion of reinforcing steel, deficiencies in design and construction method, especially the adverse stress state of the bridge due to the inadequate construction way in the formation of the profile of a bridge (Xie *et al*. 2007).

Cracks in Box Girder

Beyond the excessive deflection, cracking in box girder is another typical deficiency of long-span prestressed concrete box girder bridges, which is always dubbed a 'complication' of excessive deflection and initiates the 'cracking-deflection-cracking' cycle in bridges. As a matter of fact, cracks of the concrete lower the stiffness of the girder resulting in an increase of deflection as well as a redistribution of the internal force on the bridge, which in turn expedite the generation of new cracks. Furthermore, the crack forms the routine to transport the outside harmful aggressor to the surface of the reinforcing steels or prestressing tendons, resulting in reinforcing steels or prestressing tendons corrosion and threating the safety of the bridge.

In 2012, a survey was made on 180 prestressed concrete box girder bridges with a main span greater than 60m (196.85 ft) bridges by the Research Institute of the Highway Ministry of Transport in China and the cracks were divided into five categories depending on their position. The ratios of the number of bridges with cracks to the total number of bridges under investigation are shown in table 2 (Zhang 2012). The details of the five kinds of cracks are summarized for the seven investigated long-span prestressed concrete bridges in Table 3. All the bridges in Table 3 are continuous rigid frame categories with single-cell box section. Except for the Second Bridge of Xiangtan Xiangjiang for which two construction methods, cantilever assembling and casting, are adopted, all the others use one construction method cantilever casting.

Table 2 Percentige of cracks in diferent position of the box girder of bridges

Position	Web	Top slab	Bottom slab	Diaphragm plate	Dental plate
Percentige	86.4%	90.9%	54.5%	86.4%	36.4%

Table 3 Cracks description of seven selected long-span prestressed concrete bridges investigated

No.	Bridge	Location	Completion	Span/m	Cracks description	Served time/year
1	The Second Bridge of	Hunan	1993	50+5×90+50	The maximum length of single crack in web and top, bottom slab is	7

	Xiangtan Xiangjiang				2.2m and 8.5m. The maximum wedth of crack is 0.4mm.	
2	Huangshi Yangtze River Bridge	Hubei	1995	162.5+3×245 +162.5	There is a plenty of diagonal cracks in webs near the ends. The number of cracks inside the box gider more than the outside.	7
3	Sanmenxia Yellow River Highway Bridge	Shanxi to Henan	1992	105+4×140 +105	Diagonal cracks in webs distributes in the ends of the side span and range of L / 4.	10
4	Jinsha Bridge	Guangdong	1994	66+120+66	A large number of inclined cracks in webs.	6
5	Dongming Yellow River Bridge	Shandong	1993	75+7×120+75	The maximum wedth of crack is 0.69mm.	10
6	Fenglingdu Yellow River Bridge	Shanxi	1994	87+7×114+87	The maximum wedth of crack is 0.75mm.	14
7	Luoxi Bridge	Guangdong	1988	65+125+180 +110	The maximum wedth of cracks in web, top slab and bottom slab are 0.8mm, 1.8mm and 0.11mm.	17

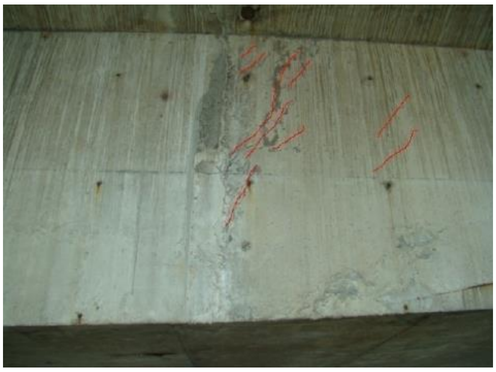
Extensive site investigation reveals that, in general, seven kinds of typical cracks in a box girder can occur in the box girder based on the position, stress state and so on, that are (Zhan and Chen 2005; Zhong 2006; Liu 2009; Feng 2009):

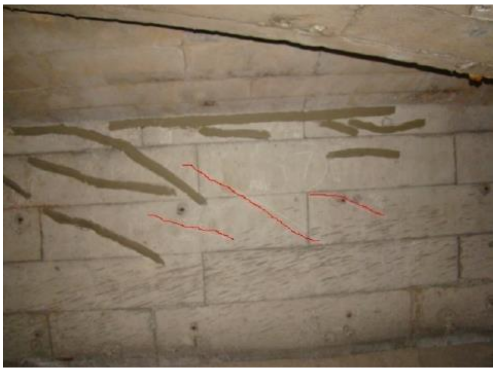
- cracks in web,
- cracks in top slab,
- cracks in bottom slab,
- cracks in diaphragm plate and radial cracks at the edge of manhole,
- cracks in dental plate,
- splitting cracks under the anchorage,
- cracks along the longitudinal duct of prestressing tendon.

Of the above type of cracks, the most dangerous one is the diagonal crack in webs for the long-span prestressed concrete box girder bridges (Song and Zhu 2008; Pan 2013).

Cracks in box girder web

The diagonal cracks in the web occur in the region around 1 / 4 span to the ends or pivot of the pier, with an angle of 25-50 degree with the axial line of the girder (Gu and Peng 2004; Peng 2011), as shown in figure 1. This kind of crack is perpendicular to the direction of the principal tensile stress, reflecting an insufficiency in the shear resistance of the girder.





a) Outside of box cell b) Inside of box cell

Figure 1 Diagonal cracks in web of girder

One of the main causes of cracks in the web may attribute to the loss of vertical effective prestressing (Jia and Peng 2006; Deng *et al*. 2007). The principal tensile stress of girder is sensitive to the existence of vertical prestressing force and the stress level (Yuan 2006; Li 2003; Zhu *et al*. 2006). However, during construction, the actual vertical effective prestressing may not reach the expected design value as it is affected by a variety of factors, such as anchorage deformation, retraction of tendons, deviation of anchorage plate, not attaining the anticipated stress level, insufficient strength of concrete during prestressing and corrosion of prestressing tendons, coupling with the action of temperature, shrinkage and creep and so on. In addition, insufficient consideration of the torsional shear stress caused by the vehicle load, as well as the combined action of the longitudinal and the transverse stress, insufficient structural fatigue strength, uneven force in the two side of the web of the box girder, improper construction procedure and overload in the operation are also important aspects affecting the cracking of the web box girder (Song and Zhu 2008; Wang and Fang 2006).

Cracks in top slab and bottom slab

The cracks, including longitudinal and transverse cracks, in the top and bottom slab of prestressed box girders are more common (Wang *et al*. 2008; Yuan 2006). Both the longitudinal and transverse cracks reflect the insufficient capability of crack resistance of each slab. Longitudinal cracks in the top slab and transverse cracks in the bottom slab are shown in figures 2 and 3 respectively.

The causes responsible for the formation of longitudinal cracks include:
- insufficient transverse effective prestress or excessive transverse prestressing loss,
- deviation of transverse prestressing tendons,
- insufficient consideration for the radial force resulting from the longitudinal prestress,
- thermal stress caused by cement hydration during construction.

The causes resulting in transverse crack include:
- insufficient longitudinal effective prestress or excessive longitudinal prestressing loss,
- underestimation of shrinkage and creep by theoretical prediction,
- insufficient consideration on shear lag effect, leading to a higher section stress peak than the average (Qiao 2011).


Figure 2 Longitudinal cracks in top slab

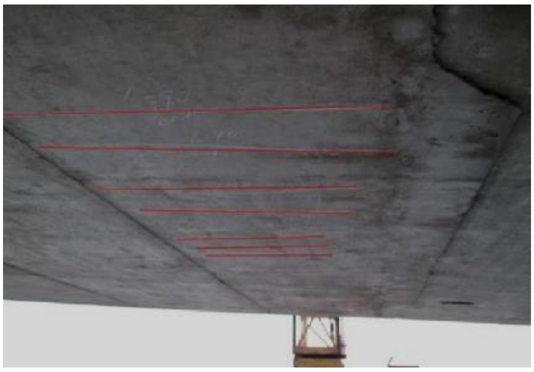


Figure 3 Transverse cracks in bottom slab

Wires Corrosion

Stay cable, main cable and suspenders are some of the main elements for cable-stayed bridge and suspension bridge respectively. They are usually exposed to the adverse environment and sensitive to corrosion because of high working stress. Albeit intensive and protective measures and steps are taken, damage and defects are found in routine and specific inspections. In the 1970s and 1980s, two-barrier corrosion protective system, prestressing strand inside polyethylene (PE) sheath injects with cement slurry and polymer-modified cement slurry, had been widely used. For this system, the anchoring zone is a deficiency-prone region, and many other problems may occur in the cement slurry grouting process, for instance, cracking in PE sheath due to higher grouting pressure and shrinkage of PE sheath with the decrease in ambient temperature, defects resulting from cement slurry grouting in separate stages and damping after solidification, insufficient grouting, cement paste segregation, all of which may induce the corrosion of the wire or strand, stress corrosion, corrosion fatigue and so on. Corrosion cases of stay cables and suspenders are listed in tables 4 and 5 respectively.

Table 4 Cable corrosion of several cable-stayed bridges in China

No.	Name	Comp-letion	Span/m	Corrosion situation	Desciption	Served time/year

1	Jiujiang Bridge	1988	13×16+40+6×50+2×160+13×50+40+7×16	About 70% of sheaths were damaged and over 30% of wires corroded and broken. Both ends of the anchor heads corroded seriously.	Single pylon cable stayed bridge with double inclined cable, ordinary prestrssing wire and hot extruded LDPE sheath.	11
2	Haiyin Bridge	1988	85.5+175+85.5	Cable 15 fallen off, cable 9 relaxed. Insufficient grouting of cement slurry in the range of 3m to the end of the cable. Wires corroded seriously.	Double pylon cable stayed bridge with single inclined cable, 3-cell box section, high strength galvanized steel wires and prestressing strand inside PE sheath injected with cement slurry and polymer-modified cement slurry.	7
3	Yellow River Bridge	1982	40+94+220+94+40	In the inspection of 1986, aluminum sheaths splitting and rusty spots on wires were detected and then treated. In 1990, cable wires corroded severely with a depth of 42mm on occasion. Some wires relaxed.	Double pylon cable stayed bridge with double inclined cable, galvanized steel wires and prestressing strand inside PE sheath injected with cement slurry and polymer-modified cement slurry.	14
4	Sanshui Bridge	1996	180+110	Cracks occurred in 27 inner sheaths. The original protective material in ducts aged. 34% of ducts were in ponding.	Single pylon cable stayed bridge with dissymmetrical double inclined cable and hot extruded PE sheath covered with orange PU protection layer.	8
5	Jianwei Minjiang Bridge	1990	52+66+240+66+52	PE sheath was fractured. Profile of the bridge was somewhat changed. 56.2% of wires corroded and 17.2% broken.	Double H-type pylon cable stayed bridge with double inclined cable, 3-cell box section and hot extrusion PE sheath.	9
6	Bayi Great Bridge	1997	50+2×160+3×50+3×50+2×160+50	Microcracks could be found in all the cable coating, and 15 cables severely cracked. Corrosion, spalling of concrete and ponding occurred in some anchor heads.	Double pylon cable stayed bridge with double fan-type cable plan and PE sheath.	10
7	BaiSha-Zhou Yangtze River Bridge	2000	50+180+618+180+50	Severe damage of cable sheaths occurred, and several high strength steel wires exposed to air and rusted. Ponding and rust could be found in anchors and embedded pipes.	Double pylon cable stayed bridge with double cable, high strength galvanized steel wires and HDPE sheath.	6
8	Panora-mio Bridge	2001	40.5+136+320+136+40.5	Sheath cracking could be found in 127 cables out of 192. Corrosion occurred in cable wires and anchorages. Stress in some cables exceeded the limits.	Double pylon cable stayed bridge with single inclined cable, wrapped with glass and polyester filament at the inner layer and hot extrusion PE sheath in the outer layer.	7
9	Fuling Yangtze River Bridge	1997	149+330+149	Various degrees of damage occurred in 73% cables and 84% cable sheaths, and 94% anchor heads. For the anchor heads, 399 were suffering from 8 kinds of	Double pylon cable stayed bridge with double cable, Π-type section of girder, suspension system with sperated pylon and girder.	9

				damage, including rust in sealing cover and penetration of water.		
10	Linjiang-men Bridge	1994	9×30+2×132.5+6.52	Cracking, breakage and aging occurred in sheaths. Some anchor heads and wires in anchorage zone corroded.	Single pylon cable stayed bridge with double fan-type cable plan, galvanized steel strands covered with glass fiber cloth and hot extrusion HDPE sheath.	—

Table 5 Cable corrosion of several suspension bridges in China

No.	Name	Compl-etion	Span/m	Description of corrosion	Description of bridge	Served time/year
1	Nanpan-jiang Bridge	1998	18.5+24.1+3×20.5+240+4×20.5	Spalling of paint and corrosion occured in most anchorage zone of suspenders. The steel plate for fixing the main cable saddle corroded and bolts thereof missing on occasion.	The main cable are 19×97 ϕ5 parallel high-strength galvanized steel wire tendons, 39 pairs of suspenders (61 ϕ 7 steel wires) in total, rise-span ratio is 1/11.	5
2	Xiling Yangtze River Bridge	1996	255+900+225	The entire protective coating system of the main cable deteriorated, including peeling and spalling, resulting in water entering the cable sleeve.	110 × 91 ϕ 5 high-strength galvanized steel wire tendons for main cable, polyisobutylene putty and polyisobutylene putty wrapped with round wires, rise-span ratio is 1/10.465.	—
3	Fengdu Yangtze River Bridge	1997	164.5+450+130	No corrosion prevention measures were taken inside the cable saddle and the external coating aged and spalled. Anchor rods seriously corroded. The depth of water in anchor chamber was over 1m and the relative humidity was more than 70%.	61 × 91 high-strength galvanized steel wire tendons for main cable, rise-span ratio is 1/11.	16
4	Wujiang Bridge	1997	66+60+168+60+66	Isabelline rust stain on the surface of main cable in midspan was clear, and water vapor could be found inside the sleeve and corrosion products deposited on steel wires. Almost all the screws and nuts on the lower end of suspender were corroded.	Each suspension cable consists of 85 parallel steel wires with PE sheath.	—
5	Jiangyin Yangtze River Bridge	1999	336.5+1385+309	Various degrees of corrosion occurred in cable wires and many wires broken.	Steel wire rope for suspender with hot extrusion PE sheath.	10

PRECAUTIONARY AND TREATMENT MEASURES

Excessive Deflections of Main Girder and Cracks in Girder

Design

Further research should be made to improve the design of long-span prestressed concrete box girder bridges, including a calculation method considering spatial effects and long-time deflection, enhancement of rigidity of superstructure. Particularly, reasonable arrangement of prestressing tendons is an important aspect need to investigated further (Xie *et al*. 2007).

It is crucial to adopt a proper shrinkage and creep model for predicting the long-time deflection of prestressed box girder bridges in design. Bažant (2012) concluded by studying the Koror-Babeldaob Bridge that poor material model for creep and shrinkage is one of the main causes of underestimation of deflection and prestress loss. Besides, it is important to select appropriate parameters relating to the prediction of prestressing loss. Enlarging frictional coefficient appropriately, setting reasonable camber and reserving tendons for remediation are other measures.

Environmental temperature change plays an important role for the long-time deflection and cracking of prestressed box girder of bridge. So, refined analysis of thermal effect is important in design. In addition, the inclined crack resistance can be improved by providing transverse prestressing tendons in the cell box and bend-up reinforcements in the web (Ren 2007).

It is effective to reduce long-time deflection by increasing the depth-span ratio appropriately (Qi *et al*. 2007). This is because, firstly, the stiffness of the main girder is enhanced and the stress state in the section is improved, secondly, the efficiency of prestressing is raised owing to the increase of the eccentricity of longitudinal prestressing tendons in the case of tendons percentage keeping constant (Pan 2013; Song and Zhu 2008). Increasing the number of the cells in the box girder, reducing the span to width ratio of the bridge and the height of the pylon are benefit to minimize the shear lag effect.

Construction

The following are some tips for reducing the long-time deflection and cracking of prestressed box girders of a bridge associated with construction:
1. Guarantee sufficient vibration of concrete and the construction quality.
2. Pay attention to the treatment of joints, ensuring the roughness of the interface.
3. Load concrete as late as possible. Don't stack too many construction materials on deck.
4. Position the corrugated pipe accurately and smoothly.
5. Ensure the prestressing force reaching preset control value, especially the vertical prestressing tendons.
6. Control the accuracy of bridge deck camber.
7. Drag the prestressing tendons as late as possible in permission of construction time to avoid excessive prestressing loss caused by creep of early-age concrete (Zhou 2013). Grout in time after prestressing tendons dragging.

Operation management

Overspeed and overload of vehicles on the bridge should be strictly prohibited. Periodic inspection mechanism should be established and regular maintenance should be strengthened. Once a deficiency is found, the causes should be clarified and the severity should be assessed. In some situation, the damage should be repaired on time, for example, cracks in concrete.

Cable Protection

The type of cable, suspender and anchorage should be selected and reliable measures of protection and vibration absorbing system should be adopted appropriately. Protection of the PE sheath should be taken and repaired timely in case of damage. In order to prevent the anchorage from corrosion, the exposed parts of anchorage ends should be coated with special rust cement and stainless steel waterproof covers should be installed (Liang 2008; Guo *et al*. 2009; Tao 2010). Steel duct should be sealed up by filling with special materials such as polyurethane foamed plastic. To isolate anchorages from water vapor and corrosive elements, sealing collars should be installed and sealed with water stopping silica gel (He 2002; Ye and Zhong 2005). Regular inspection and maintenance strategy should be made and carried out.

CONCLUTION

On basis of a great amount of literature and survey reports, a clarification is made on typical damage and deficiencies observed in the superstructures of long-span bridges in China, and the causes are identified. It is manifested that the prestressing loss, shrinkage and creep of concrete, cracking of concrete and corrosion of reinforcing steel in concrete are all accountable for the excessive long-time deflection of girders. A decrease in effective prestressing is one of the major agents that cause typical cracks in box girders, while the damage to the PE sheath in transportation, installation and ageing in operation are responsible for the corrosion of stay cables and suspenders. As a matter of fact, numerous factors are related to the deterioration of performance of long-span bridges and more challenges lie ahead for tackling the related problems. Thus, great effort should be made on in-depth research, refined designs and construction, as well as maintenance and rehabilitation.

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